RELAX: Resolution Enhancement by Laser-spectrum Adjusted Exposure

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ABSTRACT

In this work, we demonstrate a resolution enhancement technique for DUV lithography in which the light source spectrum is modified in order to improve the imaging performance of given device patterns. With this technique, termed RELAX, the imaging depth of focus (DOF) can be improved significantly for contact holes, and potentially line-space patterns. The improvement in the DOF comes at the expense of modest deterioration of other process performance metrics, such as exposure latitude and exposure bias, due to reduced image contrast at best focus. Compared to the FLEX-based techniques, RELAX allows a continuum of tunable spectral conditions without the drawback of multiple exposure passes, which is especially critical for step-and-scan lithography. Spectrum modification is accomplished by replacing the line narrowing and wavemeter modules of the excimer laser light source with RELAX-enabled modules. Direct wavefront modification of the laser output has been demonstrated to provide the optimum method for producing a double peak spectrum, which simulation has shown to produce the maximum DOF benefit. Results from imaging experiments of attenuated-PSM contact structures exposed using 248nm dipole illumination showed DOF improvements of up to 70% with a double peak separation of about 2pm. Lateral chromatic effects at this separation were negligible. These results agreed well with previous double exposure experiments[1] and simulations of some of the design structures. The process improvements were obtained without a need for re-biasing of the mask structures, although a dose adjustment was required.

Keywords: lithography, depth of focus, resolution enhancement, excimer lasers

1. INTRODUCTION

Depth of Focus (DOF) has continued to shrink as critical dimensions have decreased and lens numerical aperture has increased. While new processes such as anti-reflective coatings (ARC) and Chemical Mechanical Polishing (CMP) have allowed reduced focus budgets, DOF continues to be one of the most challenging problems in process development, particularly for contact and via layer imaging.

The FLEX concept for DOF enhancement was introduced in the late 1980s[2]. This method uses double exposures with a focus offset between the exposures to increase the image contrast at the defocus conditions at the expense of some loss of contrast, and hence exposure latitude, at best focus. At the time this method was introduced, gaining DOF was a poor trade-off for exposure latitude in most processes. Typically, large exposure latitude was required for sufficient CD control over the wide of range of resist film thicknesses caused by the large topography present on wafers before the introduction of CMP. However, recently, the FLEX method has been re-evaluated, because small DOF is now a greater challenge than exposure latitude, at reasonable levels of image contrast. The original FLEX concept has required modification due to the use of scanning exposures. Moving the focal plane during exposure is not feasible and a double pass exposure is required to produce the two focal planes, with consequent loss of throughput.

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One solution is to incline the image plane within the scanning slit to produce a range of focus settings during a single scan. However, the focus distribution in this case is different from a double focal plane exposure and it can be shown that, although some DOF improvement is obtained, it is not as optimum as exposing with two distinct focal planes.

While it is difficult to mechanically adjust focus during a scanned exposure, the axial chromatic aberration in todayís deep-UV projection lenses allows focal plane adjustment using wavelength control within the light source. This method has been called RELAX, for Resolution Enhancement by Laser spectrum Adjusted eXposure. The effect of light source wavelength, bandwidth and spectral shape on imaging has been investigated previously. [3,4,5] It was shown that simple spectral broadening provided small improvements in DOF, similar to the tilted stage approach mentioned above. However, greater improvements in DOF are obtained by generating two distinct focal planes by creating a spectrum with two wavelength peaks. This approach was investigated, without modification of the light source, by using double exposures with a wavelength shift between exposures. This experiment showed significant improvements in DOF[1] but the main drawback of this approach is clearly the loss of productivity associated with the double exposure requirement.

The dual focal planes can be obtained by producing the appropriate spectral shape by modification of the design of the wavelength control module in the laser light source. The target spectrum can be created by several different methods. These include adjusting wavelength on a pulse-by-pulse basis to build up the spectral shape over an integrated scan window. However, this method does not produce the ideal spectral shape. Alternatively, it is possible to produce the more desirable double peak spectrum in each laser pulse by wavefront modification. It can be shown that the optimum benefits in terms of DOF enhancement are obtained from a double peak spectrum with low energy at the mean wavelength. This approach also avoids the complications of synchronization to the stage scanning and laser firing, which are major issues when synthesizing the spectrum by pulse-pulse wavelength slewing. In this work, a prototype RELAX module, which creates a double peak by wavefront modification, with adjustable peak separation, was used.

2. EXPERIMENTAL

Exposures were carried out on a Canon ES4 KrF scanner with lens numerical aperture of 0.80. A Via level photomask from a Flash Memory device design was used for evaluation. This mask was an attenuated Phase Shift Mask with a transmission of 6%. Three types of contacts were inspected. The first was an arrayed contact, which had a design size of 180nm and was targeted to print at 150nm. Since this contact array had a pitch of 240nm in the horizontal direction and 480nm in the vertical direction, dipole illumination was used with a pole inner/outer sigma of 0.5/0.75. A semi-isolated contact, with a design size of 268nm x 174nm, and an isolated 180nm contact were also measured. All contacts were measured at the center and edge of the exposure field, and in both vertical and horizontal directions. The resist process used 350nm of JSR M296Y resist with NFC TARC on 64nm AR3 BARC on oxide substrates.

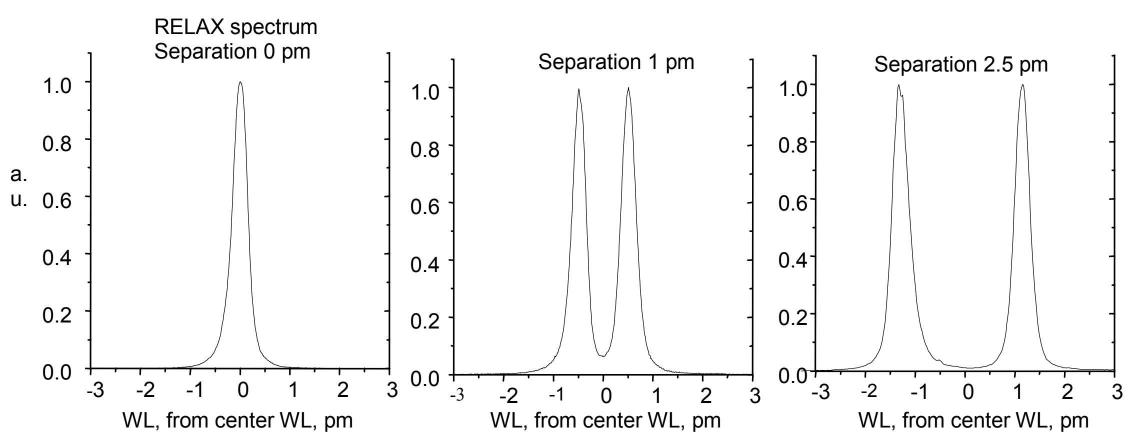

Figure 1. RELAX spectra

The RELAX spectra were created by replacing the conventional Line Narrowing Module (LNM) with a prototype RELAX LNM in the Cymer 6300 KrF excimer laser light source. This module was capable of producing a standard spectrum or a RELAX double peak spectrum with adjustable peak separations up to 6pm. In this work, the target peak separation for the test mask design ranged from 1.0 to 2.5pm, based on simulation studies. Spectral metrology of the light source output was carried out using an external LTB ELIAS II grating spectrometer. A portion of the laser beam was extracted from a modified Wavelength Stabilization Module (WSM). The external spectrometer provided detail of the complete spectral shape, which is not possible using the conventional on-board etalon spectrometer.

Measured spectra are shown in Figure 1. The RELAX module with zero peak separation actually produces a bandwidth which is slightly smaller than that from an equivalent non-RELAX module. As shown, the peak separation is well controlled, with good symmetry between the two peaks in terms of peak intensity, total energy density and bandwidth.

3. SIMULATION RESULTS

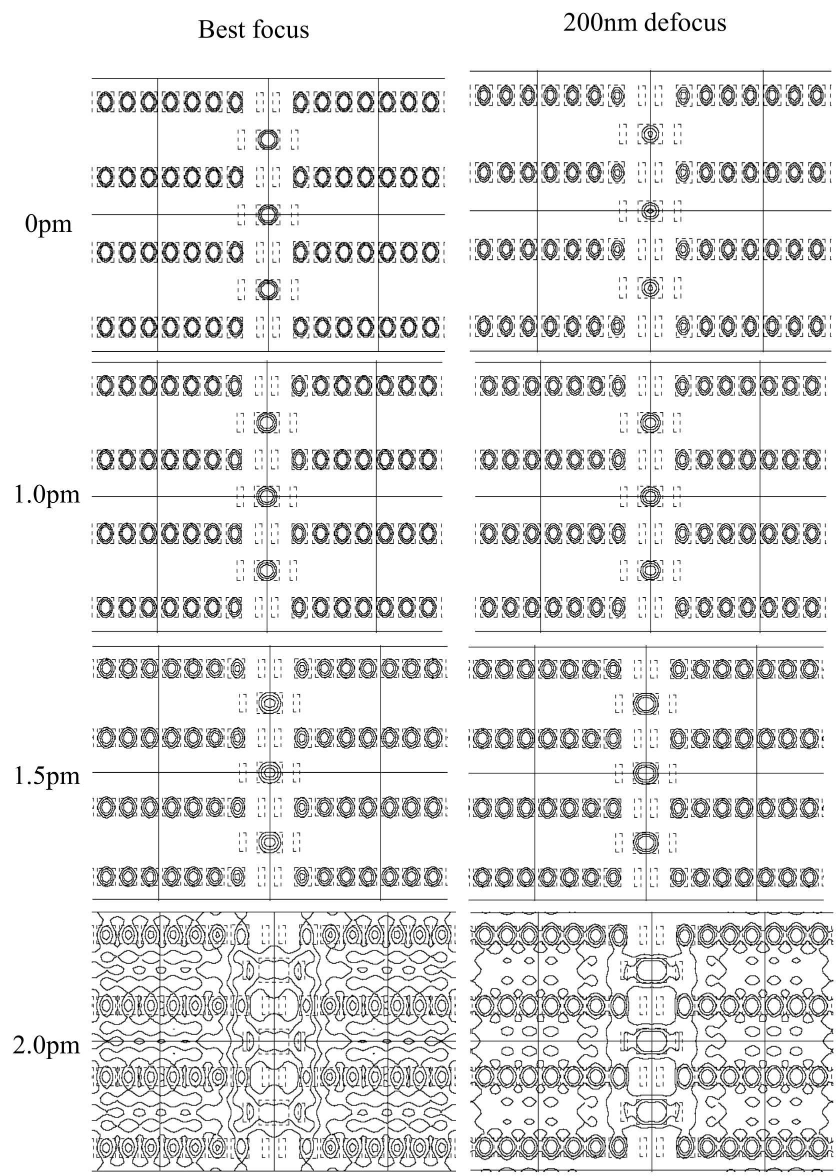

Figure 2. 2D simulation results for varying RELAX peak separation

Simulations were carried out using Canon proprietary simulation software. The calculations used a scalar approximation and CD was determined from the aerial image threshold. All lens design residual aberrations with chromatic dependence were included in the simulation. The spectral input was assumed to be monochromatic (i.e. no bandwidth), which has been shown to be a good approximation in the past.

The simulation results are shown in Figures 2-4. Figure 2 shows 2D images of the exposed Via pattern at best focus and at 200nm defocus for a number of different RELAX peak separations. It is clear that the image contrast at best focus is degraded slightly as peak separation increases but that contrast of the defocused image is improved. It can be observed qualitatively that there is an optimum RELAX peak separation at about 1.5pm, with degrading contrast at higher separation. The CD-focus curves in Figure 3 and process windows in Figure 4 were derived from these results. Figure 3 shows that CD is maintained within specification at higher defocus values as peak separation increases for all four conditions. If the peak separation is too large, the curves show a characteristic double maximum, which leads to reduced process margin. The charts in Figure 3 include both center and edge of field CD simulations but this is not easily visible because the difference between them is negligible, indicating a very small effect due to lateral chromatic aberration in this lens. Due to this particular pattern and illumination condition, some differences are observed between the arrayed and semi-isolated contacts and between vertical and horizontal CD results. These differences are clearer in Figure 4. For example, the semi-isolated contacts show degrading process window at smaller peak separation than the arrayed contact, with less DOF improvement.

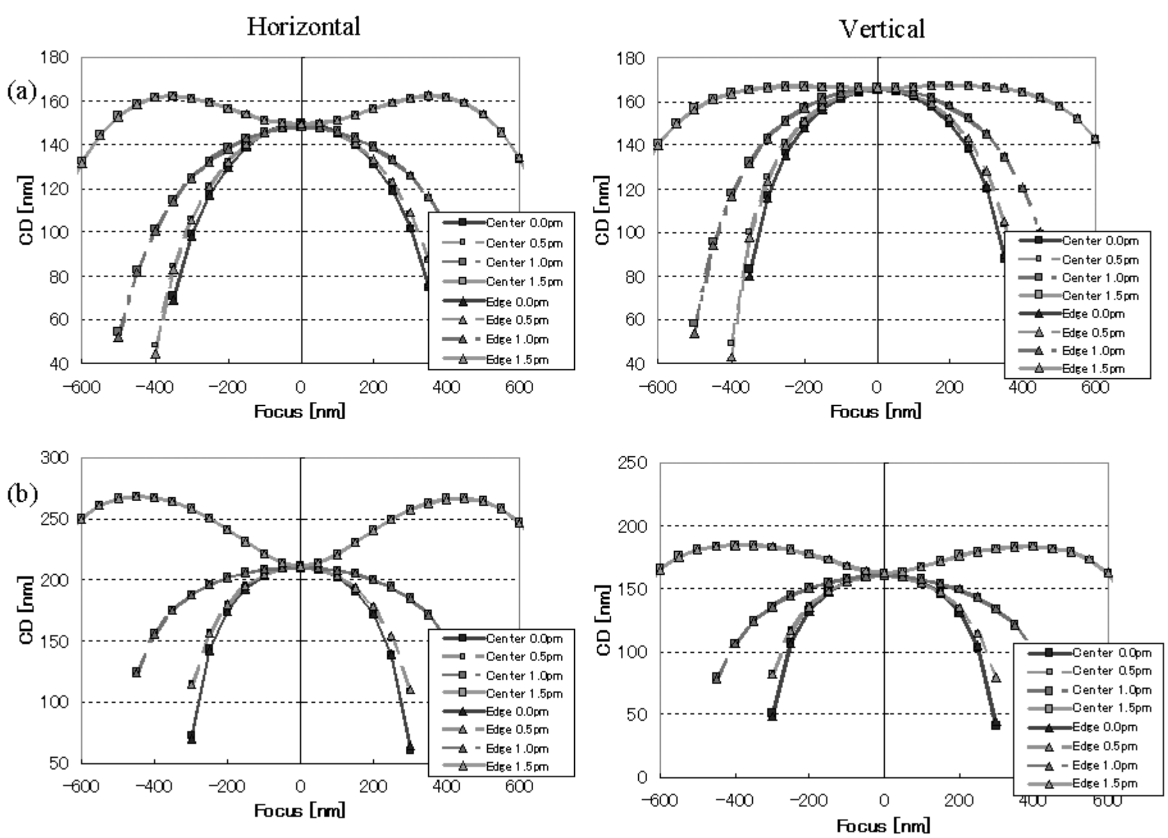

Figure 3. CD-Focus simulation results, (a) Arrayed contacts, (b) Semi-isolated contacts

4. EXPERIMENTAL RESULTS

After the RELAX module was inserted on the laser, a number of scanner diagnostics were carried out to confirm that the scanner performance was not affected by the performance of the new module. It was shown that, at any RELAX peak separation, illumination power, illumination uniformity, and focus were all unchanged. The scanner focus calibration system also functioned normally at any peak separation. CD-focus data was also compared between the standard module and the RELAX module with zero peak separation and found to be unchanged.

SEM CD measurements were taken independently in the vertical and horizontal direction at optimum dose for the different contact types. Agreement between measured dimensions and simulated CDs, including the bias between different structures, in both vertical and horizontal directions, was very good, with discrepancies of less than 3nm. Due to small errors in setting best focus and best exposure at the center of the wafer, the full through-focus and through-exposure data could not be collected in some cases. In order to analyze the DOF results, a second order polynomial fit was made to some of the data and the DOF was calculated from an algorithm using the fit parameters. Only data which could be fitted with an $R^2 > 0.9$ was used in further analysis. Typical data is shown in Figure 5.

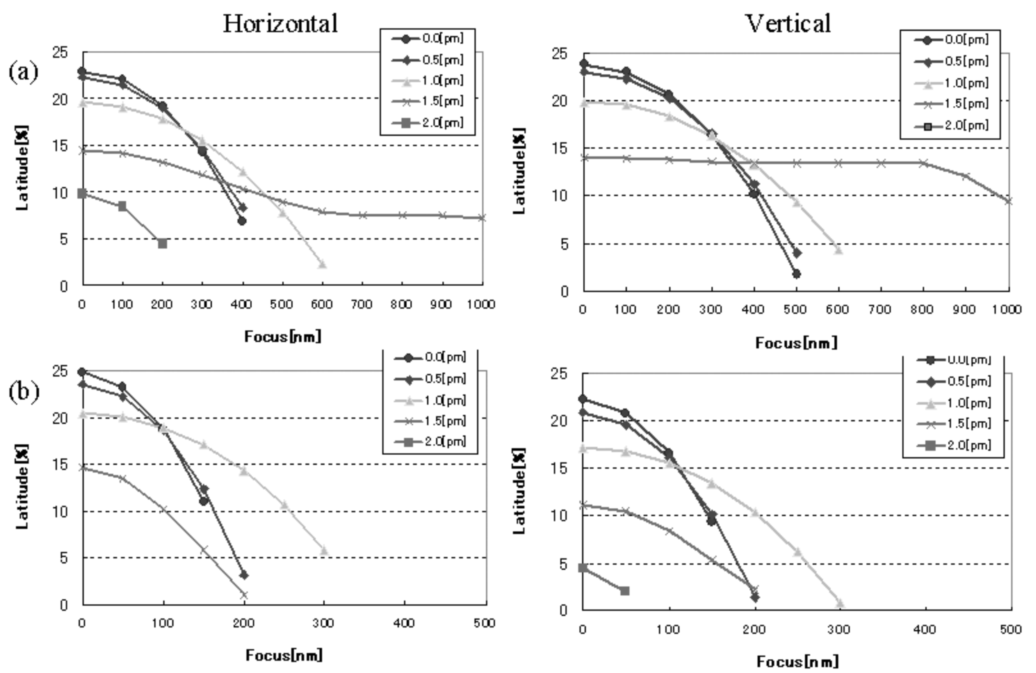

Figure 4. Process window simulation results, (a) Arrayed contacts, (b) Semi-isolated contacts

The DOF improvement from using the RELAX method is evident for all contact types, despite some missing data at the focus extremes. The DOF summary results are shown in Figure 6, for vertical and horizontal measurements taken at the center of the field. The arrayed contacts show the maximum improvement in DOF, from 320nm to about 550nm, an increase of 230nm or about 70%. The initial DOF is somewhat lower than the simulation result, but this may be due to the difference between aerial image simulation and resist imaging process latitude results. There is excellent agreement between this DOF increase and previous double exposure experimental results[1]. Both show between 200 and 250nm DOF improvement. The semi-isolated contacts show slightly less DOF improvement, with an increase of 150-20nm or about 30-40%. With regard to optimum RELAX peak separation, Figure 6 shows some differences between vertical and horizontal directions and between arrayed and semi-isolated contacts. While this may be expected due to the dipole illumination and proximity effect, there is some discrepancy between the

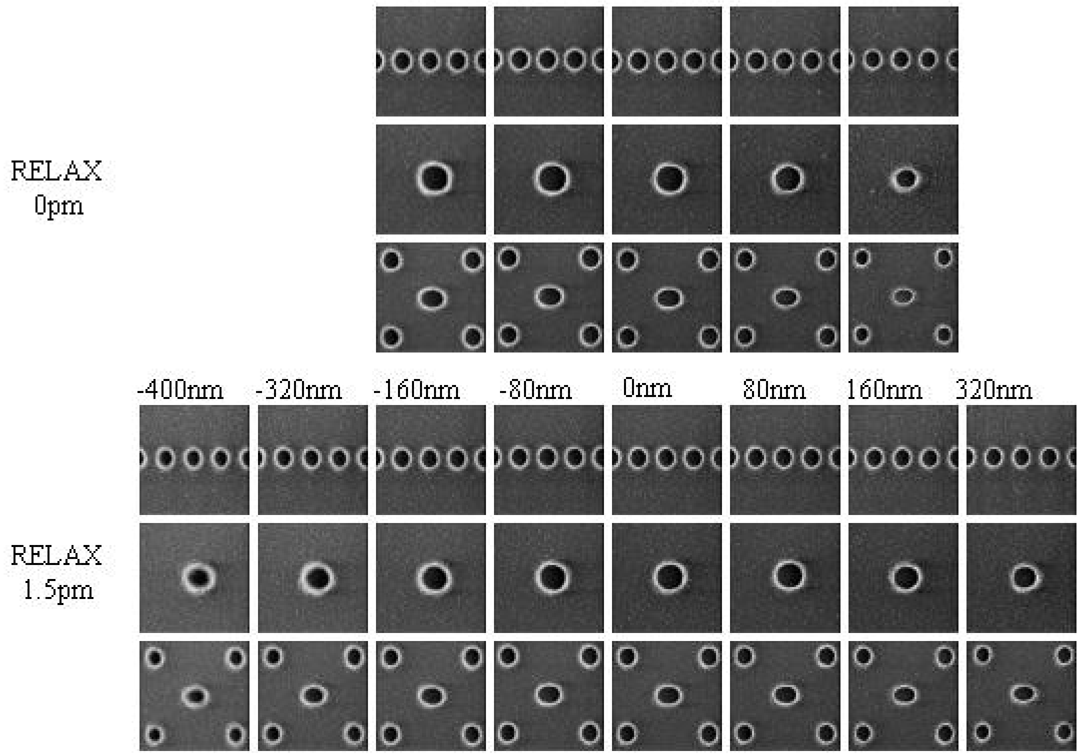

Figure 5. Top-down SEM micrographs of contact images with and without RELAX

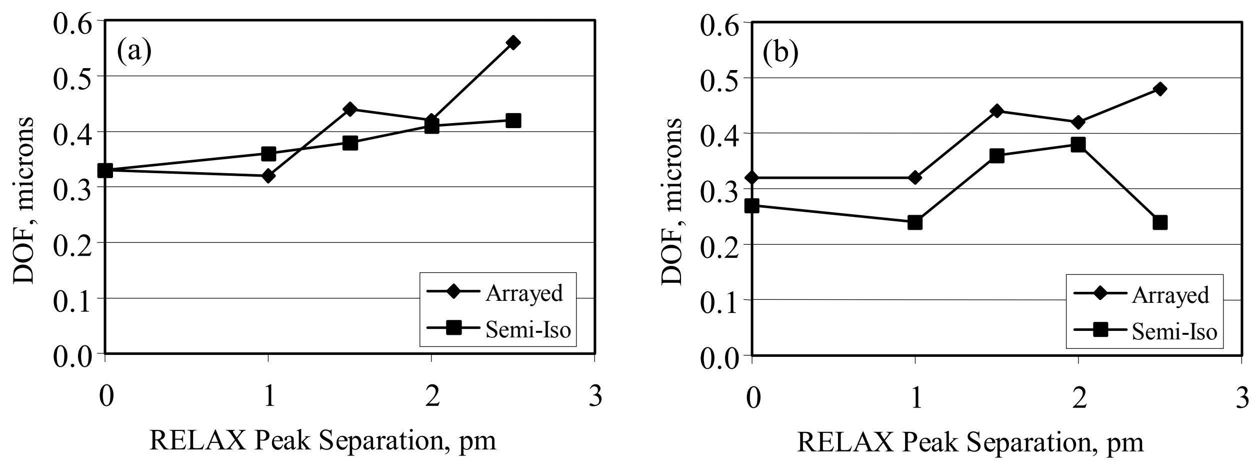

Figure 6. DOF results for arrayed and semi-isolated contacts, (a) Vertical, (b) Horizontal

experimental and simulation results. Both the present data and the previous double exposure results show an optimum at 2.0pm or above, for all cases, whereas the simulations show an optimum between 1.0pm and 1.5pm. However, the simulations appear to predict trends accurately, such as the lowest optimum peak separation for the horizontal semi-isolated contacts and the lower DOF improvement for the semi-isolated contacts. The cause of this difference is still under investigation, but may be due to the use of non-zero bandwidth in the simulation spectra. However, it is clear that a peak separation can be chosen for improved imaging for both types of contacts, independent of orientation. Full process window data could not be obtained from the wafers examined so far and further measurement and analysis is ongoing.

As seen in the simulation results of Figure 2 and experimental results in Figure 5, another indication of the optimum RELAX peak separation, and a possible drawback when imaging at reduced contrast is a loss of roundness of the contact image. Figure 7 shows the difference in CD between the vertical and horizontal CD measurements for both contact types at different RELAX peak separations. As expected, the ellipticity increases with peak separation but the change is small and represents less than 10% in both cases. This does not appear to be a significant issue in this case.

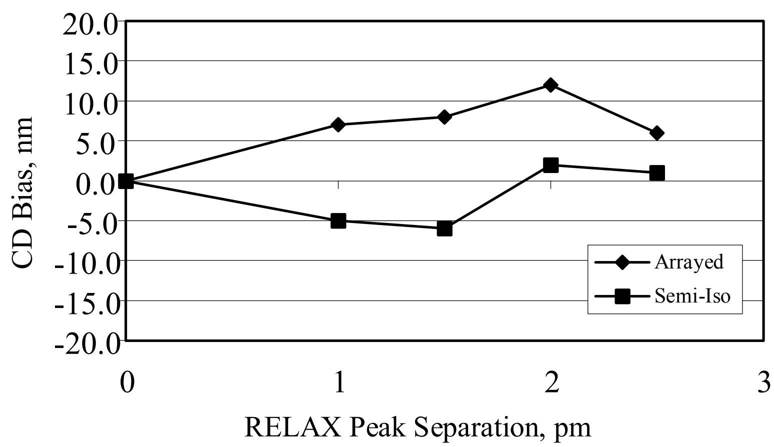

Figure 7. Contact ellipticity (Vertical-Horizontal CD)

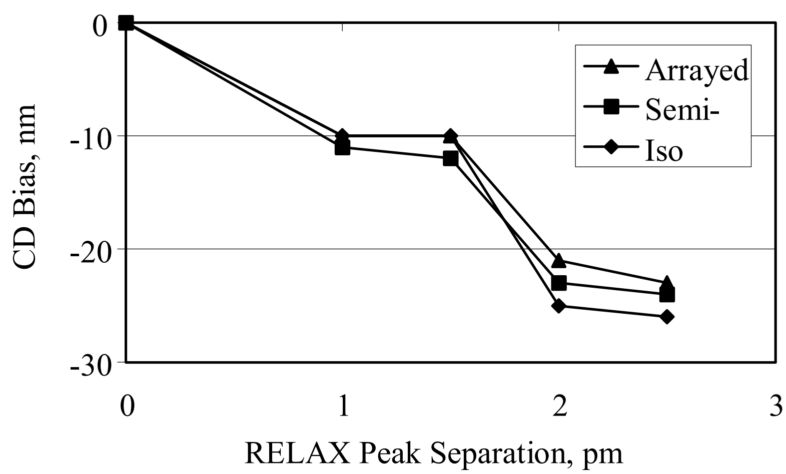

Figure 8. Effect of RELAX on CD dose bias

CD bias measurement results, at fixed dose, are shown in Figure 8, for horizontal measurements at the center of the field and at different RELAX conditions. It can be seen that the CD decreases with increasing RELAX peak separation for all three contact types. It is also observed that the change in bias is about the same for all contacts, with a maximum deviation less than 4nm. Measurements at different doses show that between 10-15% higher dose is required to re-size the contacts. This agrees well with the previous double exposure experiments, which showed an 8-14% required dose increase. Such a small dose increase is not expected to reduce throughput.

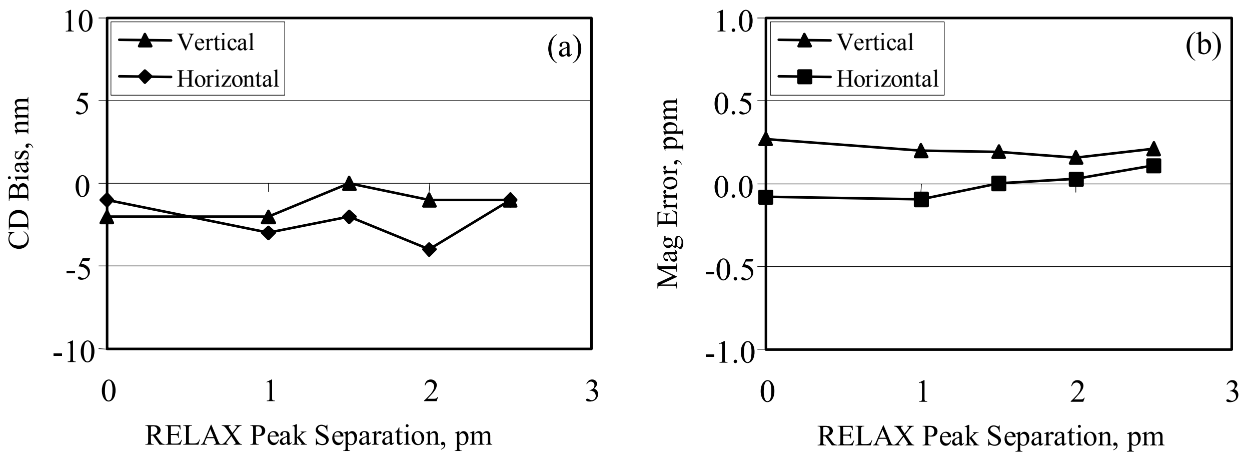

Figure 9. (a) CD bias from the center to edge of the field, (b) Horizontal magnification error

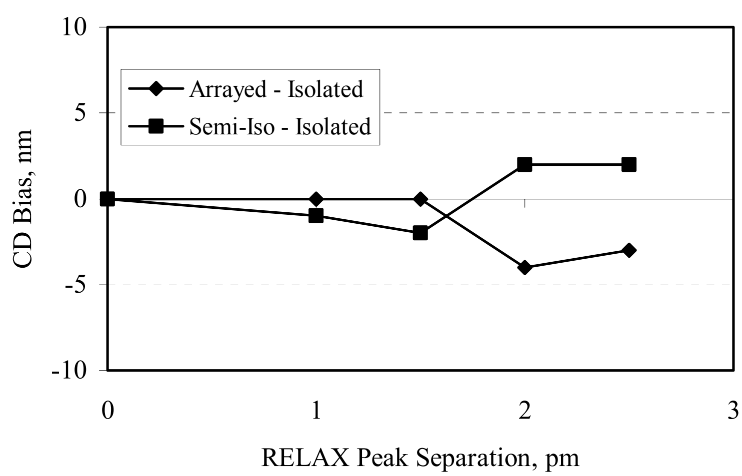

Figure 10. Effect of RELAX on proximity bias

Another potential issue with changing wavelength to produce the RELAX spectrum is the potential effect of lateral chromatic aberration, which is largest at the edge of the scan field and will depend on the magnitude of the residual aberration in the projection lens design. Although this is not expected to produce an image shift, due to the symmetry of the two wavelength peaks about the nominal wavelength, a loss of contrast and consequently a CD change may be expected. The simulations indicated a negligible effect but this was examined by measuring the CD bias between the center of the field and edge of field.

Results are shown for the arrayed contacts in Figure 9(a), including both vertical and horizontal measurements. The bias was observed to be small, <4nm, with no change due to RELAX peak separation, indicating no particular issue in this case. Although not expected, image shifts at the edge of the field were also checked by making full field overlay measurements. The results are shown in Figure 9(b), and indicate less than 0.1ppm errors.

Another potential issue with changing the imaging contrast in the RELAX process is possible variation in proximity bias. In the mask design used here, the contact proximity varied from densest, the horizontal arrayed contact dimension, through semi-isolated to isolated. The CD bias between the isolated contact and the other two features is shown in Figure 10. In both cases, there appears to be no trend in the bias with RELAX peak separation and the variation in bias is less than 4nm. Although full evaluation of overlapping process windows, currently in progress, is required to make a conclusive determination of the need for reoptimization of the Optical Proximity Correction for this design, this result and the dose bias data of Figure 8 indicate that this may not be necessary. If some small changes are needed, it may be possible to make these corrections by adjusting dose and/or illumination conditions, and these approaches are currently under investigation.

5. CONCLUSIONS

We have demonstrated a resolution enhancement technique, termed RELAX, for improving DOF for contacts by modifying the light source spectrum to simultaneously image with two focal planes. We have shown that the light source can be modified to generate an adjustable spectral shape, which can be used to successfully image both focal planes in a single exposure pass. We have confirmed that the DOF improvements previously observed in double exposure experiments can also be obtained using a conventional single-pass exposure process. DOF improvement of up to 70% was observed for a 248nm process using attenuated-PSM and dipole illumination, in fair agreement with simulation. The improvement in the DOF comes at the expense of a 10-15% increase in dose. Lateral chromatic effects at this separation were shown to be negligible, with less than 0.1ppm image shift at the edge of the field and a cross-field CD bias of less than 4nm. CD bias between different proximity features also varied by less than 4nm indicating that no mask re-biasing is required to implement the RELAX technique. It appears that this technique offers significant benefit for process layers which have adequate exposure latitude but low DOF. The flexibility of the wavefront engineering implementation allows optimization for different feature densities with no loss of productivity.

REFERENCES

1. H. Fukuda et al., Improvement of defocus tolerance in a half-micron optical lithography by the focus latitude enhancement exposure method: Simulation and experiment, J. Vac. Sci. Technol. **B7** (4), 1989.
2. I. Lalovic et al., Effects of illumination spectral width on mask error enhancement factor and iso-dense bias in 0.6NA KrF imaging, *presented at BACUS XXI Phot. Tech. Symp., Oct. 2-5, 2001.*
3. A. Kroyan et al., Modeling the effects of excimer laser bandwidths on lithographic performance, Proc. SPIE Optical Microlithography XIV 4000, *658* (2000).
4. I. Lalovic et al., Depth of focus enhancement by wavelength modulation: Can we RELAX and improve focus latitude?, *presented at Arch Chemical 2003 INTERFACE Symposium, San Diego, CA, Sept 21-23, 2003*.
5. K.Lai et al., Understanding chromatic aberration impacts on lithographic imaging, J. Microlithography, Microfabrication and Microsystems, **Vol. 2**, Issue 2, pp.105-111, 2003

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